Electronic Signal Processing for Differential Phase Modulation Formats

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Abstract: We present simulations of novel electronic signal processing techniques that may be used to greatly improve the dispersion tolerance of DBPSK and DQPSK modulation formats by at least a factor of two.
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1. Introduction

In recent years, there has been growing interest in the use of electrical signal processing (ESP) techniques for the mitigation of optical penalties, such as chromatic dispersion [1] or PMD [2], as they offer the potential for significant cost savings compared to all-optical approaches. Although this has been a very active research topic, little has been published on the application of these techniques to the D(B/Q)PSK format, which is currently being considered as a competitive alternative to ASK for long-haul links [3] or uncompensated metro systems.

In this article, we present simulations of novel ESP techniques that may be used to greatly improve (by a factor of 2 at least) the dispersion tolerance of DBPSK and DQPSK modulation formats. These techniques include a Maximum Likelihood Sequence Estimator (MLSE) using balanced detection, an MLSE using dual input detection (separate inputs from photo-detectors) and an MLSE using joint symbol estimation for DQPSK that makes decisions on I&Q symbols, taking into account any cross-coupling caused, for example, by chromatic dispersion.

2. Electrical signal processing techniques

The technique at the heart of this work is the MLSE algorithm [4,5], which can be used in different ways, according to the modulation format. Rather than making a decision based on a single instance using a D-type, the MLSE searches through a whole sequence of bits, selecting the 'most likely' sequence. Mathematically, this is expressed as selecting the sequence (S) which maximises the probability $p(x|S)$ of generating the received data (x).

For DBPSK, the simplest approach is to use an MLSE with a single input in conjunction with a balanced detector. The A/D converters may operate at 10 or 20 Gsamples/s, providing either one or two samples/bit (for 10 Gbit/s data). The MLSE algorithm maximises the total log-likelihood probability which may be expressed as the sum of probabilities over successive bits (k):

$$\max_S \log p(x \mid S) = \max_S \sum_k \log p(x_k \mid S)\Big|_T + \left[\sum_k \log p(x_k \mid S)\Big|_{\frac{T}{2}}\right] \quad (1)$$

where the term in square brackets may be omitted when using only 1 sample/bit. Rather than using a balanced detector, the MLSE may process data from the constructive and destructive photodetectors (indicated as d1 and d2):

$$\max_S \log p(x \mid S) = \max_S \sum_k \log p(x_k \mid S)\Big|_{T;d1} + \sum_k \log p(x_k \mid S)\Big|_{T;d2} + \left[\sum_k \log p(x_k \mid S)\Big|_{\frac{T}{2};d1} + \sum_k \log p(x_k \mid S)\Big|_{\frac{T}{2};d2}\right] \quad (2)$$

where, once again, the term in square brackets may be omitted when using only 1 sample/bit.

In the case of DQPSK the situation is more complex because there are two independent channels and four photodiodes. Two independent MLSEs can be applied to the two outputs of the balanced detectors (Fig.1.a). These would each process the data channel using equation 1. Alternatively, two independent MLSEs can process the outputs from the constructive and destructive photodiodes (Fig.1.b) using equation 2. The last approach examined here uses an MLSE that makes joint decisions on the noisy data from the I channel (x) and from the Q channel (y):

$$\max_S \log p(x, y \mid S) = \max_S \sum_k \log p(x_k, y_k \mid S)\Big|_T + \left[\sum_k \log p(x_k, y_k \mid S)\Big|_{\frac{T}{2}}\right] \quad (3)$$

where $p(x_k,y_k|S)$ represents the joint probability of receiving noisy sample x_k and y_k for a sequence of symbols S. This takes into account any cross-coupling or distortion between the I and Q channels.

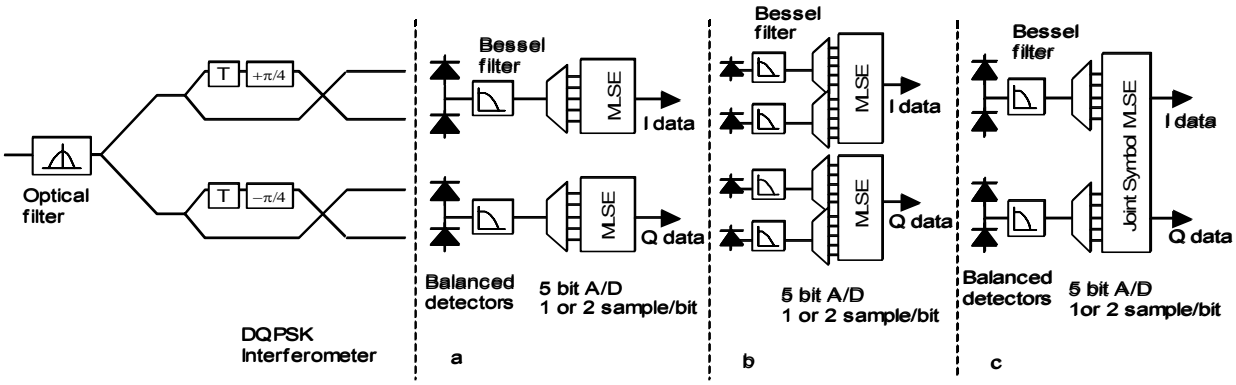


Fig.1. Receiver architecture: DQPSK interferometer followed by (a) single input MLSE using balanced detectors, (b) dual input MLSE using separate photodiodes, and (c) joint symbol MLSE using balanced detectors.

Here, we use Monte-Carlo simulations to assess the performance of these equalisers and their tolerance to chromatic dispersion. The DQPSK or DBPSK waveforms, consisting of about 100,000 bits are dispersed, noise loaded with ASE using optical amplifiers and then detected using the receivers shown in Fig.1. Non-linearity was not included in these simulations to assess the performance of the equaliser in mitigating the effect of chromatic dispersion alone. For 10 GBaud data, the optical filter has a Gaussian transfer function with a FWHM of 0.11 nm, and the electrical low pass filter is a 5th order Bessel filter with a 3 dB bandwidth of 7.5 GHz. The performance is evaluated in terms of the required OSNR (ROSNR) to achieve an output bit error ratio of 10^{-3}, which may then be corrected to 10^{-15} using strong FEC. Due to simulation limitations, the performance of the FEC is not included in this study.

The A/D converters have 5 bits quantisation resolution (32 levels), and the MLSE algorithms use either 5 bit state sequences, or 3 symbol state sequences (for joint symbol MLSE). Note that the complexity of the MLSE scales exponentially with the number of bits or symbols: a 3 symbol joint MLSE has 2^{2x3}=64 states, and a 5 symbol joint MLSE has 2^{2x5}=1024 states! In order to keep the computation complexity tractable, we consider a 3 symbol joint MLSE in the rest of this work.

Probability tables are represented by a lookup table and are trained using separate data from that used for measurement. The search for the best match is done with the Viterbi algorithm. Finally, MLSEs can operate on data sampled at the Baud rate or at a multiple of the Baud rate, for higher performance.

3. Numerical results

The results for DBPSK and DQPSK with the different receiver types are shown in figures 2 and 3, which report only positive values of chromatic dispersion for simplicity. ASK results are reported as well, as a reference.

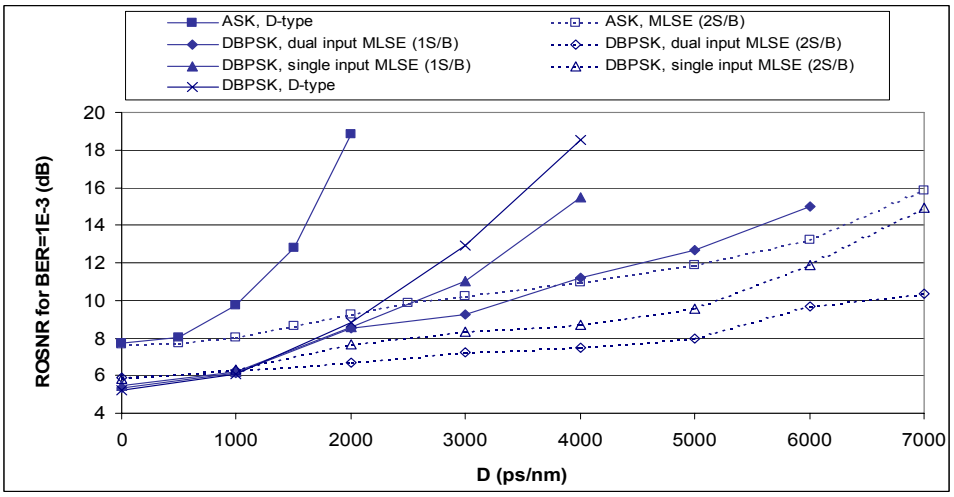


Fig. 2. Required OSNR for a BER of 10^{-3} vs. chromatic dispersion for 10 GBaud DBPSK and ASK data.

For DBPSK data (see figure 2), the improvements achieved by the MLSE algorithm depend both on the type of receiver and the number of samples per bit used. The single input MLSE using 1 sample/bit is not particularly

effective until the ISI spreads the dispersion over a neighbouring timeslot, at about 2000 ps/nm. The 3 dB tolerance of 1700 ps/nm when a D-type is used increases by a factor of 2 when a single input MLSE (2 samples/bit) is used, and by a factor of 3 with a dual input MLSE, which is superior to the achievable tolerance with ASK data and a 2 samples/bit MLSE. The phase distortion due to chromatic dispersion creates some independence in the data presented at the constructive and destructive photodiodes and results in incomplete extinction and eye closure when using a balanced detector. The independent data that is lost when using balanced detection, may be used by a dual input MLSE to provide a better chromatic dispersion tolerance.

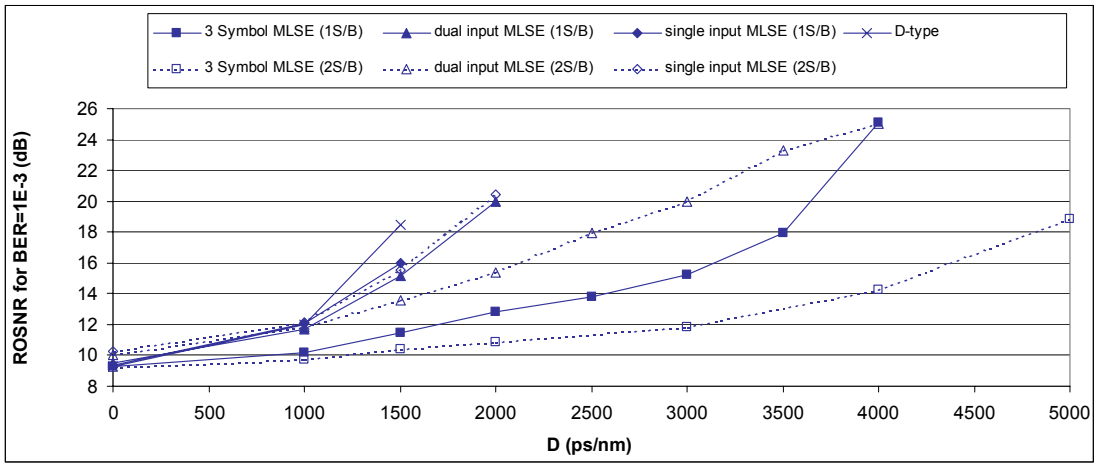


Fig 3. Required OSNR for a BER of 10^{-3} vs. chromatic dispersion for 10 GBaud DQPSK data.

It can be seen in figure 3 that for DQPSK, the MLSE using only a single input is not particularly effective in compensating for chromatic dispersion. Since the phase difference between symbols is only half that of the DBPSK, the tolerance for a 3 dB penalty is approximately half that of DBPSK when using a D-type at the receiver. For the same number of samples per bit, the best results are obtained with a joint symbol estimator, followed by a dual input MLSE and then by the single input MLSE. This figure also shows that the MLSE with 2 samples/bit always performs better than with 1 sample/bit. Compared to the simplest form of receiver (a D-type flip-flop) a 3 symbol joint MLSE with 2 samples/bit can improve the 3 dB chromatic dispersion tolerance by a factor of 3. Even with a simpler version of this device, operating on 1 sample/bit, an improvement of the 3 dB tolerance by nearly a factor of 2 can be achieved. This improvement can be explained in the following way. Without any distortion in the transmission path, the data in the I and Q channels of a DQPSK system are independent. Chromatic dispersion spreads the data over their neighbours, and modifies their phase causing coupling between the I and Q channels. A joint symbol estimator makes decisions on both I and Q channels, taking into account any cross-coupling due to chromatic dispersion.

Similar calculations performed at 5 GBaud (10 Gbit/s) indicate that the 3 dB chromatic dispersion tolerance is as high as 13000 ps/nm when a 3 joint symbol MLSE is used. This is equivalent to 760 km of NDSF or about 4640 km of NZDSF, in the absence of other system limitations such as non-linearities.

4. Conclusion

We have shown that the MLSE algorithm can be successfully applied to D(B/Q)PSK data, for an improvement of chromatic dispersion tolerance by a factor of 3. This performance is obtained with a dual input MLSE in the DBPSK case, and with a joint symbol estimation scheme in the DQPSK case. At 10 Gbit/s, the best results are obtained with DQPSK and a 3 symbol joint MLSE, for a 3 dB tolerance of 13000 ps/nm. This opens the door to differential PSK links without in-line compensation for both medium and long haul applications.

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